US LHC Accelerator Research Program
brookhaven - fermilab - berkeley

LHC Upgrades

Jim Strait
For the BNL-FNAL-LBNL LHC Accelerator Collaboration

DOE Review
10 June 2003

Outline

Luminosity Upgrades: Why and When?

Luminosity Upgrade Scenarios

The US Role in Luminosity Upgrades

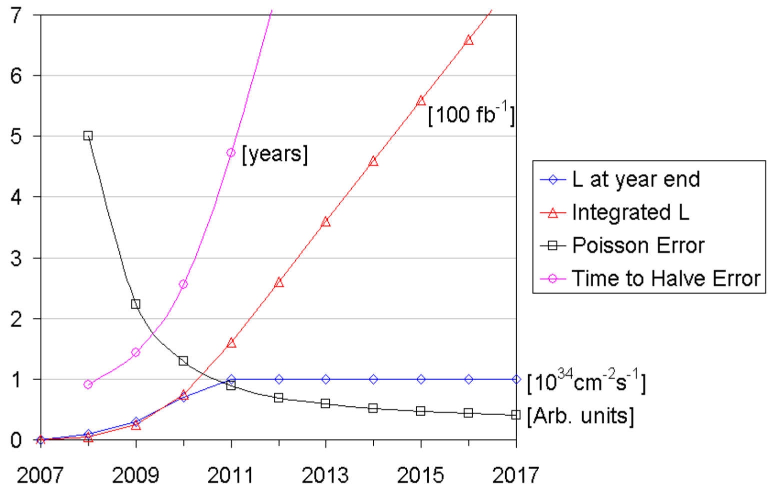
Energy Upgrades?

Conclusions

LHC Luminosity Upgrade
Why and When?

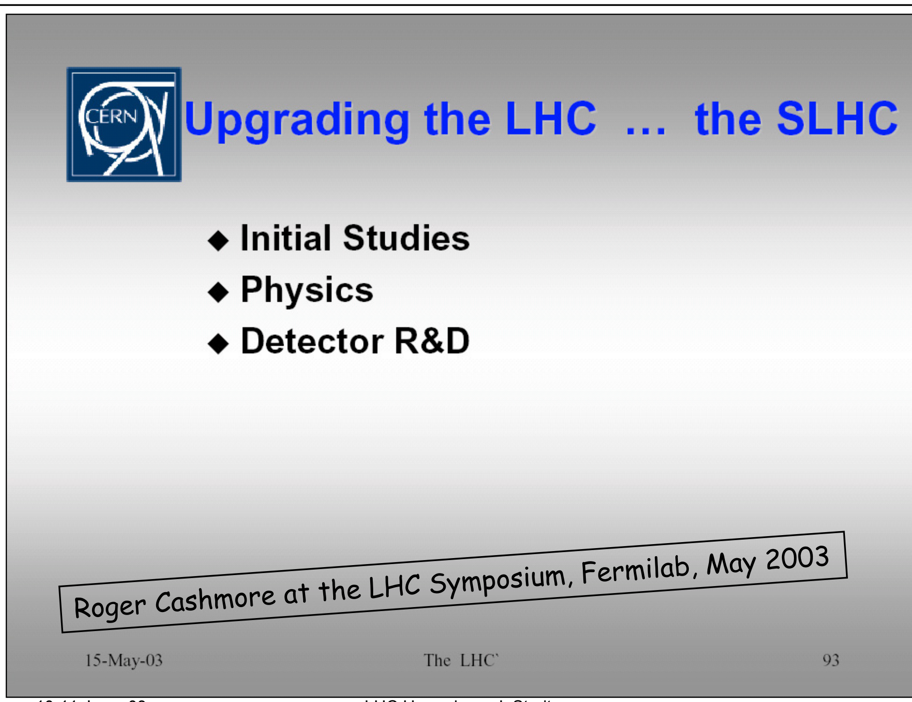
HEPAP* put R&D for a luminosity upgrade in its highest priority category:

The science of extending exploration of the energy frontier with the LHC accelerator and detector luminosity upgrades is *absolutely central*. The *R&D phase* for these will need to start soon if the upgrades are to be finished by the present target date of 2014.



*High-Energy Physics Facilities of the DOE Office of Science Twenty-Year Road Map, HEPAP report to the Director of the Office of Science, 17 March 2003.

CERN Planning for Luminosity Upgrades



Detectors: General Considerations

	LHC	SLHC
$\sqrt{s}$	14 TeV	14 TeV
L	10^{34}	10^{35}
Bunch spacing Δt	25 ns	12.5 ns *
σ_{pp} (inelastic)	~ 80 mb	~ 80 mb
N. interactions/x-ing ($N=L\,\sigma_{pp}\,\Delta t$)	~ 20	~ 100
$dN_{ch}/d\eta$ per x-ing	~ 150	~ 750
$\langle E_T \rangle$ charg. particles	~ 450 MeV	~ 450 MeV
Tracker occupancy	1	10
Pile-up noise in calo	1	~3
Dose central region	1	10

Normalised to LHC values

10^4 Gy/year R=25 cm

In a cone of radius = 0.5 there is E_T ~ 80GeV.
This will make low E_t jet triggering and reconstruction difficult.

15-May-03 The LHC` 95

Upgrade Conclusions

LHC luminosity upgrade can extend:

- physics reach of LHC at a moderate extra cost relative to initial LHC investment.
- the LHC 'lifetime'

To realise this reach, the LHC detectors must preserve performance:
trackers must be rebuilt, and
calorimeters, muon systems, triggers and DAQ need development.
Upgrades programme, from launch to data taking will take 8-10 years

The time to start is soon …. An R&D programme will be essential

Why Should We Work on a Luminosity Upgrade?

Advance High Energy Physics

- Help bring the LHC on and up to design performance quickly.
- Improve LHC performance by advances in understanding and instrumentation.
- Use LHC as a tool to gain deeper knowledge of accelerator science and technology.
- Extend LHC as a frontier HEP instrument with a timely luminosity upgrade.

Advance U.S. Accelerator Science and Technology

- Keep skills sharp by helping commission the LHC.
- Conduct forefront AP research and development.
- Advance U.S. capabilities to improve the performance of our own machines.
- Prepare U.S. scientists to design the next generation hadron collider.
- Develop technologies necessary for the next generation of hadron colliders.

Advance International Cooperation in the High Energy Accelerators

LHC Upgrade Scenarios

- LHC Phase 0: maximum performance without hardware changes
- LHC Phase 1: maximum performance with the LHC arcs unchanged
- LHC Phase 2: maximum performance with 'major' hardware changes

The nominal LHC performance at 7 TeV corresponds to a total beam-beam tune spread of 0.01, with a luminosity of $10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ in IP1 and IP5 (ATLAS and CMS), halo collisions in IP2 (ALICE) and low-luminosity in IP8 (LHC-b). The steps to reach ultimate performance without hardware changes (LHC Phase 0) are:

1. collide beams only in IP1 and IP5 with alternating H-V crossing
2. increase N_b up to the beam-beam limit $\rightarrow L = 2.3 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
3. increase the dipole field to 9 T (ultimate field) $\rightarrow E_{\max} = 7.54\,\mathrm{TeV}$

The ultimate dipole field of 9 T corresponds to a beam current limited by cryogenics and/or by beam dump considerations.

Phase 0 – Maximum $\mathcal{L}$ without Major Upgrades

parameter	symbol	units	nominal	ultimate	Piwinski
number of bunches	n_b		2808	2808	2808
bunch spacing	Δt_{sep}	ns	25	25	25
protons per bunch	N_b	10^{11}	1.1	1.7	2.6
aver. beam current	I_{av}	A	0.56	0.86	1.32
norm. tr. emittance	ε_n	μm	3.75	3.75	3.75
long. emittance	ε_L	eV s	2.5	2.5	4.0
peak RF voltage	V_{RF}	MV	16	16	3/1
RF frequency	f_{RF}	MHz	400.8	400.8	200.4/400.8
r.m.s. bunch length	σ_z	cm	7.55	7.55	15.2
r.m.s. energy spread	σ_E	10^{-4}	1.13	1.13	0.9
IBS growth time	$\tau_{x,IBS}$	h	111	72	87
beta at IP1-IP5	β^*	m	0.5	0.5	0.5
full crossing angle	θ_c	μrad	300	315	345
lumi at IP1-IP5	L	10^{34}/cm^2 s	1.0	2.3	3.6

F. Ruggiero CERN Nominal and ultimate LHC parameters at 7 TeV

LHC Phase 1: Luminosity Upgrade

Possible steps to increase the LHC luminosity with hardware changes only in the LHC insertions and/or in the injector complex include the following baseline scheme:

or smaller!

1. modify insertion quadrupoles and/or layout $\rightarrow \beta^* = 0.25\,\text{m}$
2. increase crossing angle by $\sqrt{2} \rightarrow \theta_c = 445\,\mu$rad
3. increase N_b up to ultimate intensity $\rightarrow L = 3.3 \times 10^{34}\,\text{cm}^{-2}\,\text{s}^{-1}$
4. halve σ_z with high harmonic RF system $\rightarrow L = 4.6 \times 10^{34}\,\text{cm}^{-2}\,\text{s}^{-1}$
5. double number of bunches (and increase θ_c!) $\rightarrow L = 9.2 \times 10^{34}\,\text{cm}^{-2}\,\text{s}^{-1}$ excluded by electron cloud?

Correspondingly larger $\mathcal{L}$!

Step 4 is not cheap since it requires a new RF system with 43 MV at 1.2 GHz and a power of about 11 MW/beam (estimated cost 56 MCHF). The changeover from 400 to 1200 MHz is assumed at 7 TeV, or possibly at an intermediate flat top, where stability problems may arise in view of the reduced longitudinal emittance of 1.78 eVs. The horizontal Intra-Beam Scattering growth time decreases by about $\sqrt{2}$.

F. Ruggiero CERN LHC2003, FNAL, LHC Accelerator R&D and Upgrade Scenarios

Additional $\mathcal{L}$ Upgrade Routes

parameter	symbol	units	baseline	Piwinski	super-bunch
number of bunches	n_b		2808	2808	1
bunch spacing	Δt_{sep}	ns	25	25	
protons per bunch	N_b	10^{11}	1.7	2.6	5600
aver. beam current	I_{av}	A	0.86	1.32	1.0
norm. tr. emittance	ε_n	μm	3.75	3.75	3.75
long. emittance	ε_L	eVs	1.78	2.5	15000
peak RF voltage	V_{RF}	MV	43	16	3.4
RF frequency	f_{RF}	MHz	1202.4	400.8	10
r.m.s. bunch length	σ_z	cm	3.78	7.55	7500
r.m.s. energy spread	σ_E	10^{-4}	1.60	1.13	5.8
IBS growth time	$\tau_{x,IBS}$	h	42	46	63
beta at IP1-IP5	β^*	m	0.25	0.25	0.25
full crossing angle	θ_c	μrad	445	485	1000
lumi at IP1-IP5	L	$10^{34}/\text{cm}^2\,\text{s}$	4.6	7.2	9.0

F. Ruggiero CERN Luminosity upgrade scenarios: LHC parameters at 7 TeV

US LARP

Major System Upgrades

A x10 luminosity upgrade requires upgrades to a number of accelerator systems:

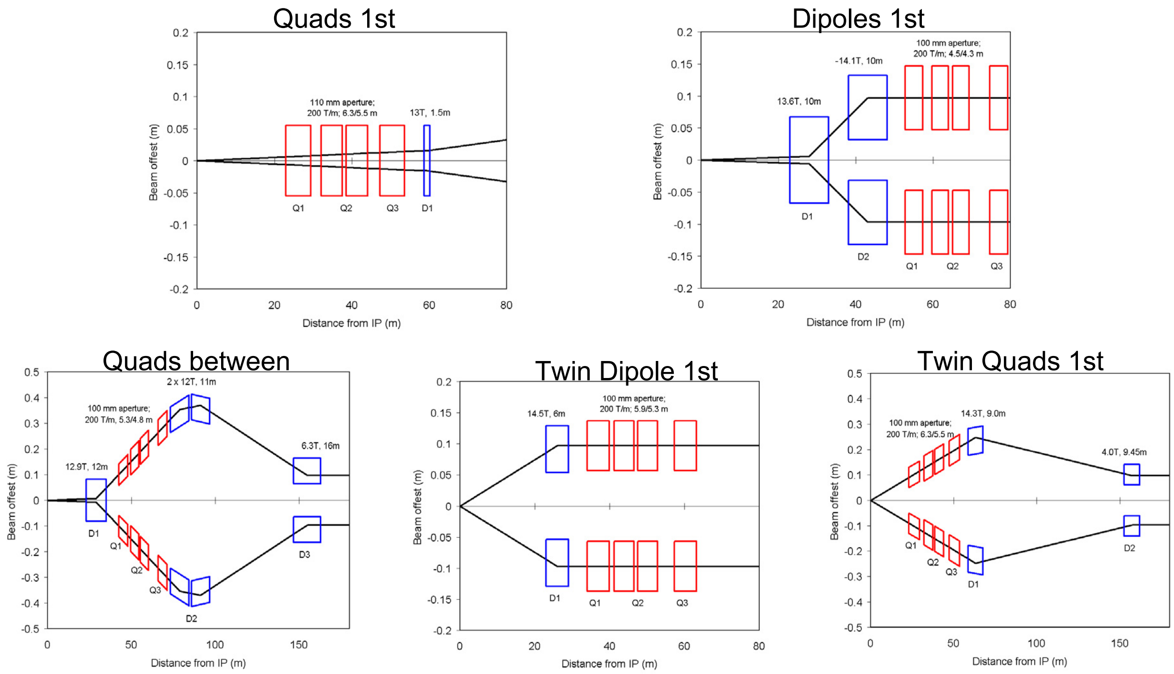
- **Interaction regions**
  => smaller β^*, larger crossing angle, fewer parasitic collisions.
- **RF system**
  => shorter bunches *or* crab cavities *or* superbunches.
- **Instrumentation, diagnostics, feedback systems**
  => understand and deal with instabilities limiting beam current.

The US LARP intends to

- Play a **leading role in the development of new IRs**.
- Make significant contributions to required **diagnostics and feedback**.

We are exploring how the US might contribute to **RF system upgrades**.

New IRs: The Major US Role in R&D for a Luminosity Upgrade



Key IR Parameters

Parameter	Luminosity Upgrade	Baseline
Quad Aperture	100 ~ 110 mm	70 mm
Peak field for G_{max}	15 T	10 T
β^*_{min}	25 cm (dipole 1st) → 10 cm (twin quads 1st)	50 cm
β_{max}	15 km (quads 1st) 23 km (other layouts)	5 km
Dipole Aperture	135 mm (dipoles 1st) → 75 mm (twin dipoles 1st)	80 mm
Dipole Field	15 T	2.75 T
Crossing angle	~0.5 mrad (single bore 1st) ~7.5 mrad (twin bore 1st)	0.3 mrad

Accelerator Physics for Luminosity Upgrade

Accelerator Physics for luminosity upgrades is the earliest AP activity.

- It informs the type of upgrade that can take place.
- It is necessary to guide the magnet R&D program, which must be launched soon and must be launched on the right path.
- Close cooperation with CERN required.

Currently planned work:

- Interaction region optics.
- Energy deposition.
- Beam-beam calculations.
- Interaction region field error compensation.
- Beam loss scenarios.
- Effects of and requirements for other machine upgrades.

Magnet R&D for a Luminosity Upgrade

- Magnet R&D will eventually become the largest part of the US LHC Accelerator Research Program.
- Plan to pursue R&D on both quadrupoles and dipoles:
  - Quads with the largest possible aperture with G_{op} > 200 T/m, required for any new IR. (FNAL + LBNL)
  - Large-aperture dipoles for the extreme radiation environment of a dipole-first IR. (BNL + LBNL)
  - Vigorous program to develop Nb_3Sn magnet technology is required.
- Deliverables will be successful R&D, leading to accelerator-ready magnet design(s), ready for production on the time scale required for for a luminosity upgrade.
- This work is a stepping stone to the magnets required for the next, higher energy hadron collider.

Energy Upgrade?

We expect that our science will require a higher energy hadron collider, once the LHC has been fully exploited.

A higher energy machine in the same tunnel is one option.

- Virtue of an "energy doubled" LHC: Uses CERN infrastructure.
- Concerns:
  - It will be expensive and require a long shutdown.
  - Nb_3Sn fundamental properties limit energy step to only < x1.8 .

HEPAP has set a lower priority on an energy than a luminosity upgrade:

> A challenging and more costly upgrade of the LHC would involve doubling the total collision energy from 14 to 28 TeV. This requires a multi-year shutdown of the machine during which the original magnets would be removed and a new collider, employing bending magnets with twice the field strength, would be installed and commissioned. It is possible that the physics found in the next decade at the LHC will be such that it will demand such an upgrade, but at this point we *don't know enough yet* either about the science or about the specifics of the facility that might be proposed. It will require an extensive *R&D phase*.

R&D Towards Higher Energy

The US Labs are the world leaders in Nb_3Sn magnets, the enabling technology for higher energy hadron colliders – EDLHC or VLHC.

Implementing the new IRs for a luminosity upgrade will be an important step in developing this technology for the colliders of the future.

- The first use of Nb_3Sn magnets in a high energy accelerator.
- In some respects they are more challenging than the main magnets of an EDLHC or VLHC.

Key issues for main magnets for a future hadron collider are being addressed by the base program:

- Push to the highest possible field (e.g. the LBNL program).
- Develop economical production techniques (e.g. the FNAL program).
- Explore alternate technologies and materials (e.g. the BNL program).

Conclusions

- A Luminosity Upgrade is a high priority goal both for US HEP and for CERN.
- The US Labs can play (and are playing already) a leading role in the R&D towards the Luminosity Upgrade.
  - AP studies of key machine issues and of new IR designs.
  - Magnet R&D for new IRs.
  - Development of instruments to understand and overcome beam limitations.
- The R&D on the Luminosity Upgrade by the US Labs will
  - Bring the upgrade into being sooner.
  - Strongly advance our capabilities in accelerator science.
  - Develop the technologies required for any future higher energy hadron collider.